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# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**A VIRTUAL ENVIRONMENT FOR RESILIENT  
INFRASTRUCTURE MODELING AND DESIGN**

by

Jens P. H. Ruether

September 2015

Thesis Advisors:

David L. Alderson

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Daniel Nussbaum

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**A VIRTUAL ENVIRONMENT FOR RESILIENT INFRASTRUCTURE  
MODELING AND DESIGN**

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Submitted in partial fulfillment of the  
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**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

from the

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## **ABSTRACT**

This thesis considers the interoperability of recent modeling efforts that apply constrained optimization (combined with representations of system function and management) to assess and improve the operational resilience of critical infrastructure (CI) systems to disruptive events. We implement these mathematical models using the Pyomo optimization package, which is built on top of the Python programming language. This computational environment provides advantages for data preprocessing and post-processing, including convenient and efficient methods for manipulating CI network data. Moreover, the object-oriented nature of Pyomo creates a natural means for representing interdependent CI systems. Specifically, the model for each CI system can be implemented as its own object, and the combined model can be implemented as another object built from its dependent components. This allows for increased flexibility and extensibility beyond previous implementations. We manage the inputs and outputs of the models in a way to be able to compare them across studies, obtaining insight on their performance, interactions, and effectiveness. This thesis supports a broader effort to build a repository of functional CI models enabled from a geospatial user interface and connected to a common, backend simulation engine.



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## **LIST OF ACRONYMS AND ABBREVIATIONS**

AD	Attacker-Defender
BBL	Barrel (42 U.S. Gallons)
CHDS	Center for Homeland Defense and Security
CI	Critical Infrastructure
CID	Center for Infrastructure Defense
CSV	Comma Separated Value
DAD	Defender-Attacker-Defender
DHS	Department of Homeland Security
EM	Electric Model
FM	Fuel Model
FM+EM	Combined Fuel Model and Electric Model
GAMS	General Algebraic Modeling System
GIS	Geographic Information System
GUI	Graphical User Interface
HR	Hour
HSC	Homeland Security Council
IDEA	Infrastructure Design Editor Analyzer
IEEE	Institute of Electrical and Electronics Engineers
MW	Megawatt(s)
MWh	Megawatt-hour(s)
NIPP	National Infrastructure Protection Plan
NPS	Naval Postgraduate School
PCCIP	President's Commission on Critical Infrastructure Protection
PPD	Presidential Policy Directive
R&D	Research and Development
RTS-96	Reliability Test System 1996
XML	Extensible Markup Language



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## EXECUTIVE SUMMARY

Earthquakes, floods, typhoons, and climate change, as well as terrorist attacks, can cause—and have caused—damage to critical infrastructural (CI) systems. Interruptions of energy (electricity, fuel, gas) supply networks or communication (glass-fiber-optic) networks can be damaging because of our dependence on them. Moreover, a disruption in one CI system can have a cascading effect on another CI system because these systems are commonly interdependent. Because of the desire for more resilient CI systems, there is an ongoing need to develop and apply operational models of infrastructure function.

Unfortunately, previous research and development (R&D) efforts to improve infrastructure resilience have been hampered because of a lack of model interoperability, a lack of functional realism, sensitivity of real system geography or vulnerability, and/or an inability to visualize system behavior in the presence of disruptive events.

This thesis addresses the interoperability of recent modeling efforts at the Naval Postgraduate School (NPS) that apply constrained optimization (combined with representations of system function and management) to assess and improve the operational resilience of CI systems to disruptive events. We implement these mathematical models using the Pyomo optimization package, which is built on top of the Python programming language. This computational environment provides advantages for data preprocessing and post-processing, including convenient and efficient methods for manipulating and visualizing CI network data. Moreover, the object-oriented nature of Pyomo creates a natural means for representing interdependent CI systems. Specifically, the model for each CI system can be implemented as its own object, and the combined model can be implemented as another object built from its dependent components. This allows for increased flexibility and extensibility beyond previous implementations.

We consider the behavior of a notional pair of interdependent fuel and electricity infrastructure systems. We manage the inputs and outputs of the models in a way to study them in isolation or as a combined pair, obtaining insight on their performance,

interactions, and effectiveness. We validate our results against those from a previous study.

This thesis supports a broader effort to build a repository of functional CI models enabled from a geospatial user interface connected to a common, backend simulation engine.

## ACKNOWLEDGMENTS

To Jessica, my wife and soulmate forever. You are and continue to be the foundation for our marriage, family, and life. Your curiosity, patience, understanding, and love provide essential support that inspires me each and every day. Therefore, I dedicate this and the rest of my life to you and our dreams.

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## I. INTRODUCTION

Earthquakes, floods, typhoons, and climate change, as well as terrorist attacks, can and have caused damage to critical infrastructure (CI) systems. Our complex society highly relies on these systems, and therefore an effort to make them more resilient to natural or human incidents is necessary. Interruptions of energy (electricity, fuel, gas) supply networks or communication (glass-fiber-optic) networks are additionally highly dependent on each other. Therefore, optimizing usage and structure of one system realistically means optimizing the dependent systems appropriately in context. Studies dealing with optimizing networks of infrastructure used software to simulate destructive events and improve resilience.

The common concept of operational resilience for a CI system to adapt and to maintain its function in the presence of a disruptive event is introduced in “National Strategy for Homeland Security” (Homeland Security Council [HSC] 2007), which was driven by the Executive Order 13010 establishing the the U.S. President’s Commission on Critical Infrastructure Protection (PCCIP) in 1996. The process led to the Presidential Policy Directive 21 (PPD) (White House 2013), and the concept was expanded in the National Infrastructure Protection Plan (NIPP) in December 2013 by the Department of Homeland Security (DHS)

Alderson et al. (2014) describe how to build and solve a sequence of models in order to assess and improve the operational resilience of an infrastructure system for worst-case disruptions. However, in order to support real decision-makers, these analyses require two important features:

- **Functional Realism:** The behavior of the model has to be as close as possible to the function of a real infrastructure system. For example, a model of electric power transmission should reflect the laws of electromagnetics (e.g., Kirchhoff’s Laws).

- Geographical Realism: CI systems are inherently geospatial. When superimposed on a map, they should look as close as possible to a real system.

In practice, however, the use of real infrastructure system data and geography for research is often restricted to avoid revealing vulnerabilities to a potential attacker. As a result, at the moment there is an inability to share realistic infrastructure models and data, and this is hampering research and development (R&D) efforts to improve infrastructure resilience. Each study so far is a one-time result, which does not allow teaching, results in lost insights after execution and presentation, and sometimes leads to repetition of work. Additionally, there are no benchmarks for comparison of standard data sets as model inputs, standard functional models, canonical examples of resilience or brittleness, and algorithm performance.

Overcoming these barriers requires that we address several questions: How can the inputs and outputs of a CI model be standardized without loss of generality? Is it possible to use the result from one model in another to improve the results? Is there a way to incorporate different models so that solving them optimizes both models? Is there a way to compare two models that analyze the same system and get a measure of effectiveness in a way that hints at improving them?

This thesis considers the interoperability analysis of recent simulations that apply constrained optimization (combined with models of system function and management) to assess and improve the operational resilience of critical infrastructure systems to disruptive events. A goal of this research is to study interactions between models and systems and to measure effectiveness of models.

This thesis focuses on combining the results of resilience analysis of critical infrastructure using network models via a set of software solutions that integrate different types of models. We manage the inputs and outputs of the models to compare them across studies. We implement the results from one model into another using backend simulation engines to run optimization on a full-spectrum set of influences. The goal is to

build a repository of functional CI models enabled from a geospatial user interface and connected to a backend simulation engine (see Figure 1).

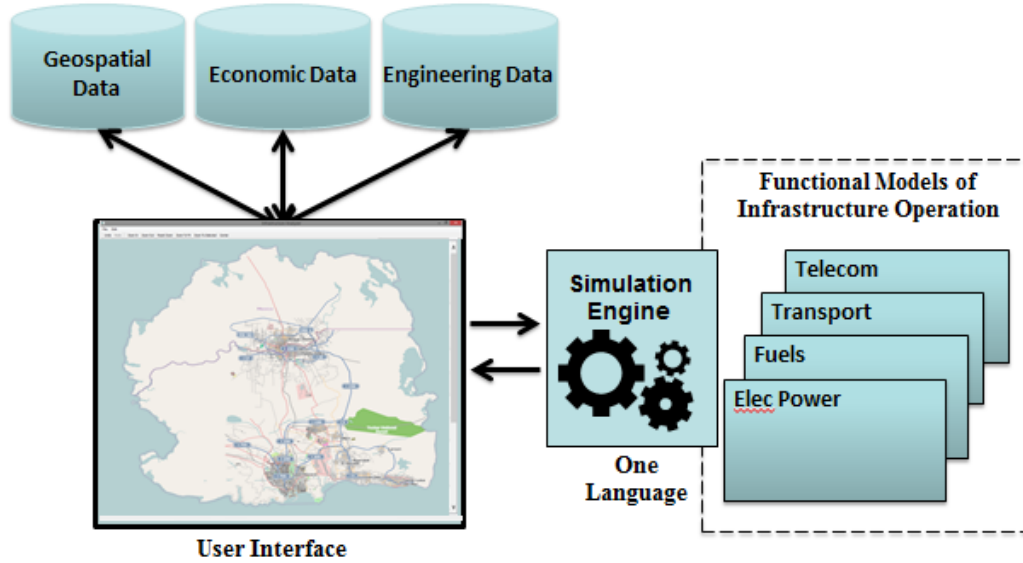


Figure 1. Integration of real-world behavior rules and operational infrastructure models via a single computational simulation engine plus visualization and interaction with it via a GUI (from Naval Postgraduate School Center for Infrastructure Defense [CID] 2013)

We apply attacker-defender models, as in Alderson et al. (2014), to problems involving interconnected infrastructure systems in the spirit of Dixon (2011) and following the mathematics developed in Dickenson (2014). We consider a geospatial computational platform as in Martin (2014). The results, performance, and usability are compared to the onetime results from previous studies.

The ultimate goal of the research is to create a sandbox for analysis, design, and virtual testing of new infrastructure systems and operation that allow what-if scenarios to system responses to disruptive events (e.g., cascading failure behavior) in a context-rich, controlled environment for exercises, education, and training on realistic CI systems. The hope is that this sandbox serves as a better environment to produce predictions about unknown interactions of the grids and to assess resilience for real systems.



Chapter II of this thesis provides a brief summary of previous work that has been done and shows the possibilities for improvement. Chapter III presents the mathematical models we use in our analysis. Chapter IV shows how we integrate interacting models into a structured and improved computational environment that enabled the user to modify their tests and get their transferable results via a GUI (graphical user interface) from a backend server. Chapter V summarizes our contribution and outlines the potential for future work.

## **II. LITERATURE REVIEW**

### **A. PREVIOUS WORK**

There already exist several models and algorithms to improve networks of infrastructure in terms of resilience. The literature on this is large and growing. A tremendous amount of work has been done by the Center for Infrastructure Defense (CID) at the Naval Postgraduate School (NPS). This chapter provides an abbreviated review of the work most relevant to this thesis, along with an outline of our contribution.

The general attacker-defender (AD) and defender-attacker-defender (DAD) models for CI are defined in Brown et al. (2006). These models help identify functional and important parts of the network and seek a solution to gain resilience by using game theory and optimization models. They consider deliberate disruptions of functional networks by intelligent adversaries. They assess worst-case effects of multiple disruptions to identify the system's ability to return to a normal state.

Salmerón et al. (2004, 2009) apply AD models to the electric power system. They implement dominant physical rules, like Kirchhoff's Laws, in a functional network that therefore allows realistic predictions of this nontrivial construct.

AD and DAD models are used to study fuel infrastructure in Alderson et al. (2015). For a notional CI system, they use a sequence of models to assess and improve operational resilience, which then can be achieved by actions like installing redundant components or capacity expansion.

The basic mathematics and modeling for interdependent infrastructure systems were created by Dixon (2011). Dixon first classifies relationships and interdependencies in the analysis of effects on CI; he then uses this data in a game-theory AD model to gain insight into otherwise unpredictable effects caused by these interactions. Finally, he provides mechanisms and procedures to use this on real-world data and shows how to give a decision-maker information that he can understand and use with network analysis procedures to get low-cost suggestions with a significant improvement in overall cost.

Dickenson (2014) expanded the work of Dixon (2011) to a larger application modeling interdependent fuel and electric power infrastructures. Dickenson formulates an algorithm to analyze dependent electric and fuel infrastructure systems using penalty functions to weight the interactions. He solves for the combined behavior of separate dependent models and compares the results to those from a single integrated monolithic model and finally gives suggestions of further improvements possible.

Martin (2014) presents a geospatial tool for infrastructure analysis. Martin develops a graphical interface to make it easier to input parameters for a minimum cost flow network problem. He focuses on the analysis of a fictional CI system, which has a geospatially and functionally realistic structure. He uses this tool to evaluate the resilience of this fictional system.

This thesis follows the basic steps for assessing and improving infrastructure resilience, as defined by Alderson et al. (2014). Their tutorial shows how to build a sequence of models to improve the resilience of CI. Disruptions can be caused by nature or human action. They use simplified examples and real-world analogies to clarify the impact and the advantages of existing models, to improve the state of being prepared, and to enhance new structures.

## **B. OUR CONTRIBUTION IN CONTEXT**

This thesis focuses on optimizing the results of resilience analysis of critical infrastructure using network models. In addition, it enables interoperability of the models and gives insight into the performance and interactions of given models. The goal is to build a repository of functional CI models enabled from a geospatial user interface and connected to a backend simulation engine.

### III. MATHEMATICAL MODELS

This thesis adopts the fuel and electric networks from Alderson et al. (2014) and Salmerón et al. (2004), respectively, to formulate a combined mathematical model as in Dickenson (2014) to allow these separate networks to interact in terms of suppliers of one system demanding a commodity of the other system.

A key building block in our analysis is a mathematical construct used by Dixon (2011). He connects supply at a node in one network to the flow on an arc in another network. As illustrated in Figure 2, flow  $Y_{ij}$  on arc  $(i,j)$  of infrastructure II depends on a flow  $V_{nij}$  from node  $n$  of infrastructure network I reaching a specific threshold.

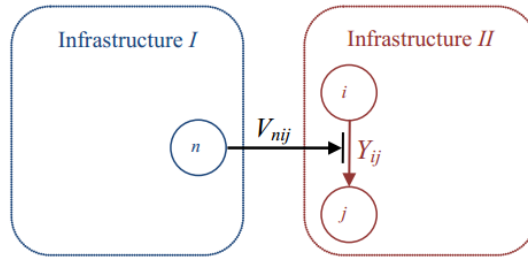


Figure 2. The requirement of a commodity from infrastructure I by infrastructure II (from Dixon 2011).

Mathematically, this dependence is represented using the following two constraints:

$$threshold_{ij} \cdot T_{ij} \leq V_{nij} \quad (1)$$

$$Y_{ij} \leq u_{ij} \cdot T_{ij} \quad (2)$$

$T_{ij}$  is a binary variable. It is used to determine whether the threshold requirement is met.  $T_{ij}$  is set to zero when the flow  $V_{nij}$  of the required commodity I is below the requirement  $threshold_{ij}$ .  $T_{ij}$  can be set to one only when  $V_{nij}$  is greater than or equal to  $threshold_{ij}$ .  $Y_{ij}$  is the flow in infrastructure II. If  $T_{ij}$  is zero, the capacity  $u_{ij}$  of arc  $(i,j)$  is

set to zero and no flow  $Y_{ij}$  is possible. If  $T_{ij}$  is one, then the capacity  $u_{ij}$  of arc  $(i,j)$  is the regular upper bound of the flow  $Y_{ij}$ .

This setup is used on all dependencies between the electric and the fuel network. The networks from Dickenson (2014) are not altered in our analysis to compare results and derive insights from the analysis.

## A. SETS, DATA, AND VARIABLES FOR OUR FORMULATIONS

For completeness and consistency, we present all index sets, data, and variables for our formulations, as originally described in Dickenson (2014).

### 1. Indices and Index Sets

$n \in FN$	nodes in fuel network (alias $f\bar{i}, f\bar{j}$ )
$n \in FD \subseteq FN$	demand nodes in fuel network
$n \in FS \subseteq FN$	supply nodes in fuel network
$FArcs \subseteq FN \times FN$	arcs in fuel network
$n \in PN$	nodes in power network (alias $p\bar{i}, p\bar{j}$ )
$n \in PD \subseteq PN$	demand nodes in power network
$n \in PG \subseteq PN$	generation (supply) nodes in power network
$n \in PI \subseteq PN$	bus nodes in power network (where supply = 0)
$PArcs \subseteq PN \times PN$	arcs in power network
$n \in PDN \subseteq PN$	power demand nodes that supply fuel components
$(f\bar{i}, f\bar{j}) \in PDFA_n \subseteq FArcs$	power-dependent fuel arcs: $(f\bar{i}, f\bar{j}) \in PDFA_n$ can carry flow if and only if power supply to $n \in PDN$ exceeds a given threshold.
$n \in FDN \subseteq FN$	fuel demand nodes that supply power components
$(p\bar{i}, p\bar{j}) \in FDPA_n \subseteq PArcs$	fuel-dependent power arcs: $(p\bar{i}, p\bar{j}) \in FDPA_n$ can carry flow if and only if fuel supply to $n \in FDN$ exceeds a given threshold

## 2. Parameters [Units]

$FSupply_n$	fuel supply at node $n \in FN$ [Barrel(bbl)/ hour(hr)]
$FLdSCost_n$	fuel load shedding cost of demand node $n \in FD$ [\$/bbl]
$FArcCost_{fi, fj}$	per-unit cost to move fuel on arc $(fi, fj)$ [\$/bbl]
$FArcCap_{fi, fj}$	capacity of fuel on arc $(fi, fj)$ [bbl/hr]
$PDem_n$	power demand at node $n$ [Megawatts(MW)]
$PArcCap_{pi, pj}$	power capacity of $(pi, pj)$ [MW]
$\widehat{PY}_{pi, pj}$	power flow across power arc $(pi, pj)$ [MW]
$PThresh_n$	power threshold required by power demand node $n \in PDN$ [MW]
$PGenCap_n$	power generator capacity of $n \in PG$ [MW]
$PGenCost_n$	power generator cost per MW by node $n \in PG$ [\$/Megawatt-hours (MWh)]
$PLdSCost_n$	power load shedding cost of node $n \in PD$ [\$/MWh]
$PArcRes_{pi, pj}$	resistance of arc $(pi, pj)$ [ohms]
$PArcRea_{pi, pj}$	reactance of arc $(pi, pj)$ [ohms]
$B_{pi, pj}$	susceptance of arc $(pi, pj)$ [1/ohms]
$\widehat{FY}_{fi, fj}$	fixed fuel flow across arc $(fi, fj)$ [bbl/hr]
$FThresh_n$	fuel threshold required by power generation node $n \in FDN$ [bbl/hr]

## 3. Decision Variables [Units]

$FY_{fi, fj}$	flow on fuel arc $(fi, fj)$ [bbl/hr]
$FLdS_n$	load shedding at fuel demand node $n \in FD$ [bbl/hr]

$$\begin{aligned}
FT_n &= \begin{cases} 1 & \text{if net supply to fuel demand node } n \in PDN \text{ meets or exceeds threshold} \\ 0 & \text{otherwise} \end{cases} \\
PGen_n & \text{ power generated at generator node } n \in PG \text{ [MW]} \\
PY_{pi,pj} & \text{ flow on power arc } (pi, pj) \text{ [MW]} \\
PLdS_n & \text{ load shedding at power demand node } n \in PD \text{ [MW]} \\
\theta_n & \text{ phase angle at power node } n \in PN \text{ [radians]} \\
PT_n &= \begin{cases} 1 & \text{if net supply to power demand node } n \in FDN \text{ meets or exceeds threshold} \\ 0 & \text{otherwise} \end{cases}
\end{aligned}$$

## B. FUEL MODEL WITH INTER-DEPENDENCE

We begin with a formulation for a fuel infrastructure system, whose pumps depend on electric power provided by a separate infrastructure.

### 1. Formulation

$$\min_{\substack{FY, FLdS \\ FT}} \sum_{(fi, fj) \in FArcs} FArcCost_{fi, fj} FY_{fi, fj} + \sum_{n \in FDN} FLdSCost_n FLdS_n \quad (F0)$$

s.t.

$$\sum_{\substack{fj: (n, fj) \\ \in FArcs}} FY_{n, fj} - \sum_{\substack{fi: (fi, n) \\ \in FArcs}} FY_{fi, n} - FLdS_n \leq FSupply_n \quad \forall n \in FN \quad (F1)$$

$$FY_{fi, fj} + FY_{fj, fi} \leq FArcCap_{fi, fj} \quad \forall (fi, fj) \in FArcs \quad (F2)$$

$$FY_{fi, fj} + FY_{fj, fi} \leq FArcCap_{fi, fj} FT_n \quad \forall n \in PDN, (fi, fj) \in PDFA_n \quad (F3)$$

$$PThresh_n FT_n \leq \sum_{pi: (pi, n) \in PArcs} \widehat{PY}_{pi, n} - \sum_{pj: (n, pj) \in PArcs} \widehat{PY}_{n, pj} \quad \forall n \in PDN \quad (F4)$$

$$FY_{fi, fj} \geq 0 \quad \forall (fi, fj) \in FArcs \quad (F5)$$

$$FT_n \in \{0, 1\} \quad \forall n \in PDN \quad (F6)$$

### 2. Discussion on Inter-dependence

Key to the functional inter-dependence are constraints (F3), (F4), and (F6) involving the variables  $FT_n$ . Each  $FT_n$  is a switch modeling the interdependence. It is set to one if the net electric supply received by demand node  $n$  within the electrical

distribution system meets or exceeds the power requirement or threshold,  $PThresh_n$ . Constraint (F3) sets the capacity of an arc of the fuel network to zero or full capacity, if the dependence threshold variables  $FT_n$  are set to zero or one. Constraint (F4) sets the dependence threshold variable  $FT_n$  based on the operating conditions in the electric system. In this model the  $FT_n$  variables are only constrained by the fixed electric flows,  $PY_{pi,n}$ , from that system. Stipulation (F6) sets the dependence threshold variables,  $FT_n$ , as binary.

### C. ELECTRIC MODEL WITH INTER-DEPENDENCE

We continue with a formulation for an electricity infrastructure, whose generators depend on the energy resources of a separate fuel infrastructure.

#### 1. Formulation

$$\min_{\substack{PY, PGen \\ PLdS}} \sum_{n \in PG} PGenCost_n PGen_n + \sum_{n \in PD} PLdSCost_n PLdS_n \quad (P0)$$

s.t.

$$PY_{pi,pj} = B_{pi,pj} (\theta_{pj} - \theta_{pi}) \quad \forall (pi, pj) \in PArcs \quad (P1)$$

$$\sum_{\substack{pi:(pi,n) \\ \in PArcs}} PY_{pi,n} - \sum_{\substack{pj:(n,pj) \\ \in PArcs}} PY_{n,pj} = 0 \quad \forall n \in PI \quad (P2)$$

$$PGen_n + \sum_{\substack{pi:(pi,n) \\ \in PArcs}} PY_{pi,n} - \sum_{\substack{pj:(n,pj) \\ \in PArcs}} PY_{n,pj} = 0 \quad \forall n \in PG \quad (P3)$$

$$\sum_{\substack{pi:(pi,n) \\ \in PArcs}} PY_{pi,n} - \sum_{\substack{pj:(n,pj) \\ \in PArcs}} PY_{n,pj} + PLdS_n = Pdem_n \quad \forall n \in PD \quad (P4)$$

$$FThresh_n PT_n \leq \sum_{\substack{fi:(fi,n) \\ \in FDPN}} \widehat{FY}_{fi,n} - \sum_{\substack{fj:(n,fj) \\ \in FDPN}} \widehat{FY}_{n,fj} \quad \forall n \in FDN \quad (P5)$$

$$PY_{pi,pj} \leq PArcCap_{pi,pj} PT_n \quad \forall n \in FDN, (pi, pj) \in FDPA_n \quad (P6)$$

$$0 \leq PY_{pi,pj} \leq PArcCap_{pi,pj} \quad \forall (pi, pj) \in PArcs \quad (P7)$$

$$0 \leq PGen_n \leq PGenCap_n \quad \forall n \in PG \quad (P8)$$

$$0 \leq PLdS_n \leq PDem_n \quad \forall n \in PD \quad (P9)$$

$$PT_n \in \{0, 1\} \quad \forall n \in FDN \quad (P10)$$



## 2. Discussion on Inter-dependence

Key to the functional inter-dependence are constraints (P5) and (P6) involving the variables  $PT_n$ . Each  $PT_n$  is a switch modeling the interdependence. It is set to one, if the net fuel supplied to demand node  $n$  in the fuel distribution system meets or exceeds its fuel requirement (threshold),  $FThresh_n$ . Constraint (P5) sets the dependence threshold variable  $PT_n$  based on the operating conditions in the fuel model. In the fuel model the  $PT_n$  variables are only constrained by the fixed fuel flows,  $\widehat{FY}_{fi,n}$ , from that system. Constraint (P6) sets the capacity of an arc of the electric network to zero or full capacity, if the dependence threshold variables  $PT_n$  are set to zero or one.

## D. COMBINED MODEL

We combine the formulations of the electricity infrastructure and the fuel infrastructure into a single, integrative model, and convert the flow parameters in the dependency constraints to variables in order to solve for optimal solution of the combined model.

### 1. Formulation

$$\begin{aligned} \min_{\substack{FY, FLdS \\ FT, PY, PY \\ PGen, PLdS}} \quad & \sum_{(fi, fj) \in FArcs} FArcCost_{fi, fj} FY_{fi, fj} + \sum_{n \in FD} FLdSCost_n FLdS_n \\ & + \sum_{n \in PG} PGenCost_n PGen_n + \sum_{n \in PD} PLdSCost_n PLdS_n \end{aligned} \quad (C0)$$

s.t.

$$(F1), (F2), (F3), (F5), (F6)$$

$$(P1), (P2), (P3), (P4), (P6), (P7), (P8), (P9), (P10)$$

$$PThresh_n FT_n \leq \sum_{\substack{pi: (pi, n) \\ \in FArcs}} PY_{pi, n} - \sum_{\substack{pj: (n, pj) \\ \in FArcs}} PY_{n, pj} \quad \forall n \in PDN \quad (C1)$$

$$FThresh_n PT_n \leq \sum_{\substack{fi: (fi, n) \\ \in FArcs}} FY_{fi, n} - \sum_{\substack{fj: (n, fj) \\ \in FArcs}} FY_{n, fj} \quad \forall n \in FDN \quad (C2)$$

## 2. Discussion on Inter-dependence

Constraints (C1) and (C2) model the interdependencies between the two systems. Constraints (C1) requires that net supply of electrical power to power demand nodes meet or exceed the threshold,  $PThresh_n$ , to allow fuel flow on the corresponding interdependent fuel arc  $(fi, fj)$ . Constraints (C2) requires that net supply of fuel to fuel demand nodes meet or exceed the threshold requirement,  $FThresh_n$ , to allow electric flow on the corresponding interdependent power arc  $(pi, pj)$ .

## E. DISCUSSION

Dickenson (2014) implemented this model using the General Algebraic Modeling System (GAMS 2015), but his implementation consists of many separate model files (see Figure 3) and is not easy to extend or modify. The results from that implementation are simple text files with no fixed format, which makes them hard to use in common statistical analysis tools like JMP (2015) or R (2015)

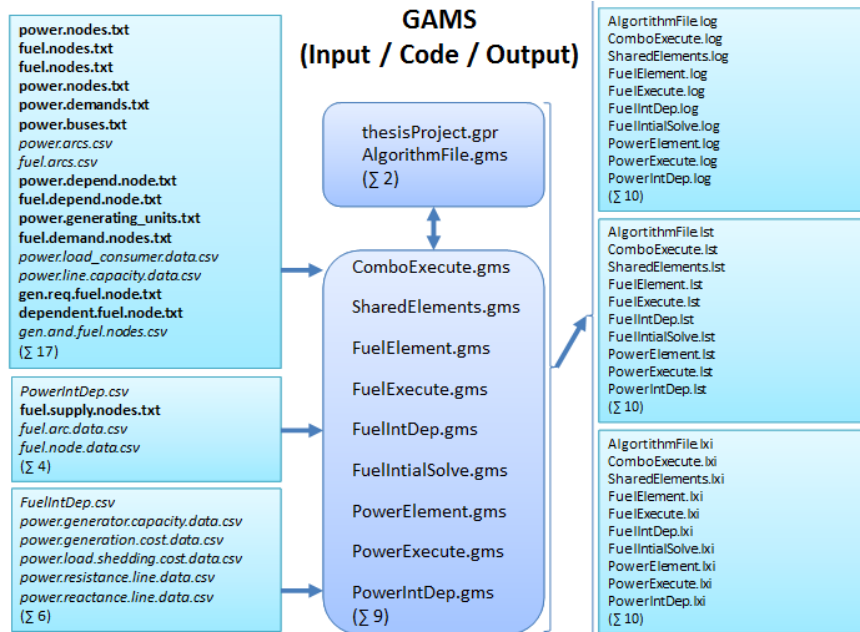


Figure 3. GAMS (.gms) code files necessary to solve the combined model and the corresponding input text and comma separated value (.csv) files as implemented in Dickenson (2014).

Building on Dickenson's basic implementation, we make several improvements to allow extension and modification of the model and allow implementation of different solvers and more advanced algorithms.

## IV. IMPLEMENTATION AND RESULTS

### A. OUR APPROACH

Dickenson (2014) demonstrates how two well-understood infrastructure networks with established, published, and proven formulations could interact in a GAMS (2015) environment. The first one is taken from Alderson et al. (2014), a fuel model with their operator formulation. The other is the IEEE (Institute of Electrical and Electronics Engineers) RTS-96 (Reliability Test System 1996) with the electric model taken from Salmerón et al. (2004). The interdependence is modeled using the constructs from Dixon (2011).

We elect to implement these mathematical models using the Pyomo optimization package (2015), which has been built on top of the Python programming language (2015). There are several reasons for this. First, a Python-based programming environment has advantages for data preprocessing, and the availability of libraries, such as NetworkX (2015), provide convenient and efficient methods for manipulating CI network data. Second, Python supports subroutines, whereas GAMS does not, and subroutines are essential for modular algorithm development. Third, the object-oriented nature of Pyomo creates a natural means of representing CI systems. Specifically, the operator model for each CI system can be implemented as its own object, and the combined model can be implemented as another object built from its dependent components. This allows for increased flexibility and extensibility beyond similar implementations in GAMS. Finally, a Python implementation allows for easier integration into other applications, specifically the Graphical User Interface (GUI) defined in Martin (2014), which was also implemented in Python. Specifically, we are able to connect our models to that GUI via a transfer file using the extensible Markup Language (XML) format (see Figure 4).

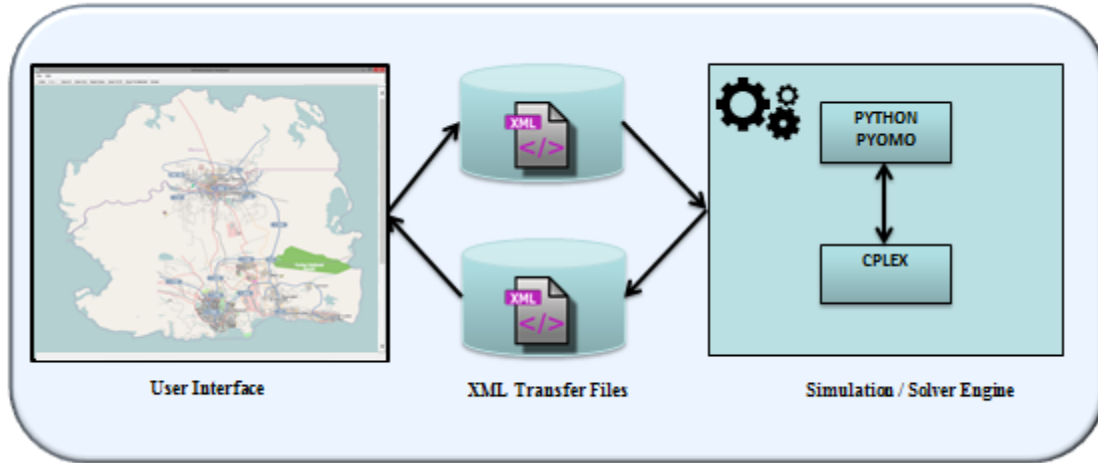


Figure 4. GUI improves usability as the translation into one program language. One type of transfer file that is universally readable improves exchange and analysis option of solution sets.

## B. FOCUS

The goal is to allow a continuous and reusable integration of mathematical models and geospatial data into a graphical representation supported by software that is extensible and low-cost. This way, all work can be reused, further improvements and deeper insights can be gained, and there is no need to reinvent a system or to relearn or reprogram already established and proven results when using them on a bigger scale or in different model environments.

## C. MILESTONES

We subdivided the project into three milestones (A, B, and C; see Figure 5). Milestone A involves using the logic of Dickenson (2014) for the separate fuel model (FM) and electric model (EM) in Python Pyomo. Milestone B involves building a combined model (model EM-FM) in an efficient way that produces the same results as the original GAMS code. Milestone C involves using the model from the GUI and improving further aspects of usability, security, transferability, and efficiency. We present results from model FM, model EM, and model FM+EM in three representative cases to compare resulting solution network flow and objective.

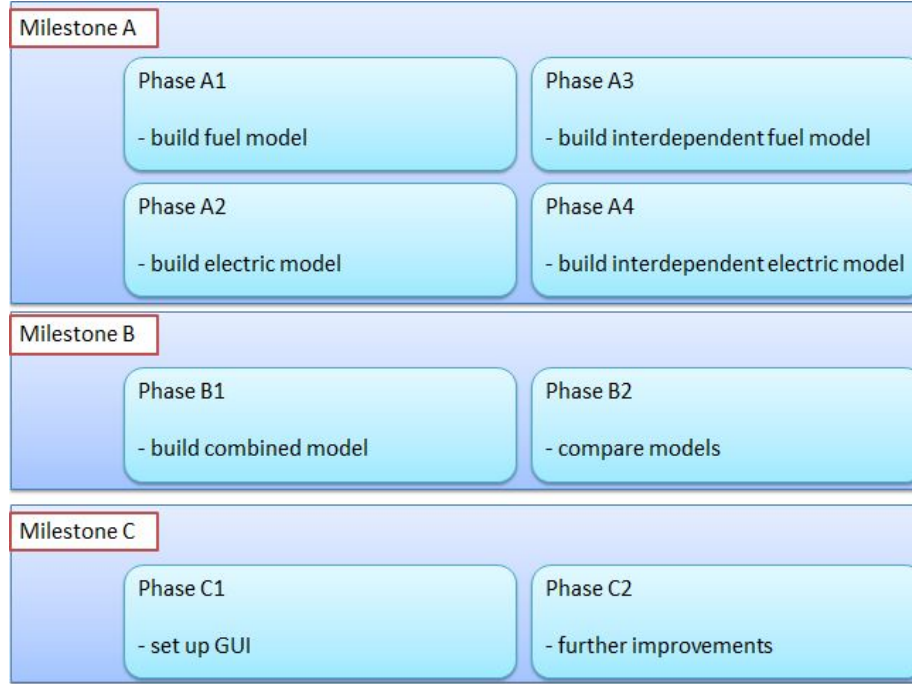


Figure 5. Milestones A, B, and C and its phases for our translation and improvement process.

## 1. Milestone A

Milestone A is a logical model in a Python Pyomo environment that implements all necessary logical steps from the FM in GAMS and the EM in GAMS.

We create a Python subroutine that uses Pyomo to build the FM, which includes all sets, all parameters, all variables, all constraints (including dependency constraints), and the objective, as defined in Section III.A of this thesis.

We build on the notional fuel infrastructure, which is introduced in Alderson et al. (2015) and shown in Figure 6 as basis for our analysis.

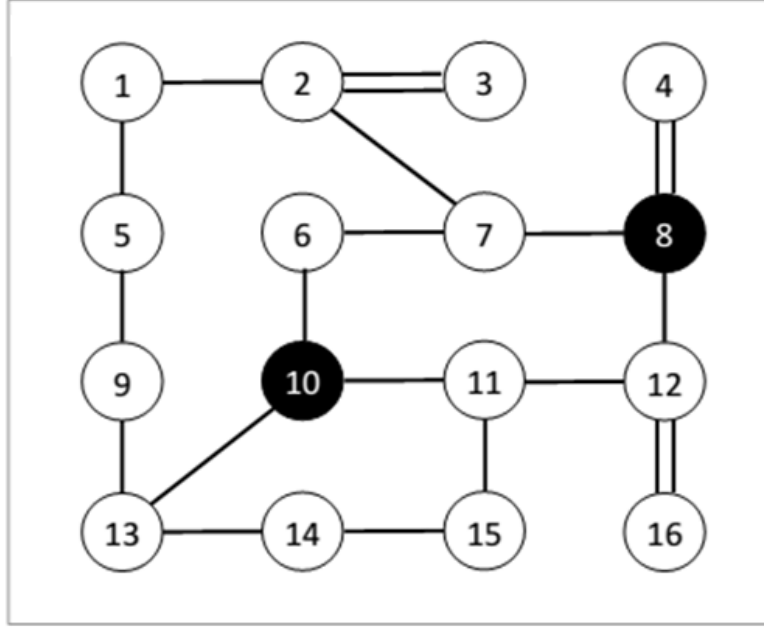


Figure 6. Fuel distribution network model where the black filled circles are the supply nodes and the others have fuel demands; the arcs represent establish connections between nodes (from Alderson et al. 2015).

We create another Python subroutine that uses Pyomo to build the EM, which includes all sets, all parameters, all variables, all constraints (including dependency constraints), and the objective, as defined in Section III.A of this thesis.

Figure 7 shows the electric system. It has 74 total nodes composed of 33 generator nodes, 17 demand nodes, and 24 bus nodes (from Reliability Test System [RTS] Task Force 1999).

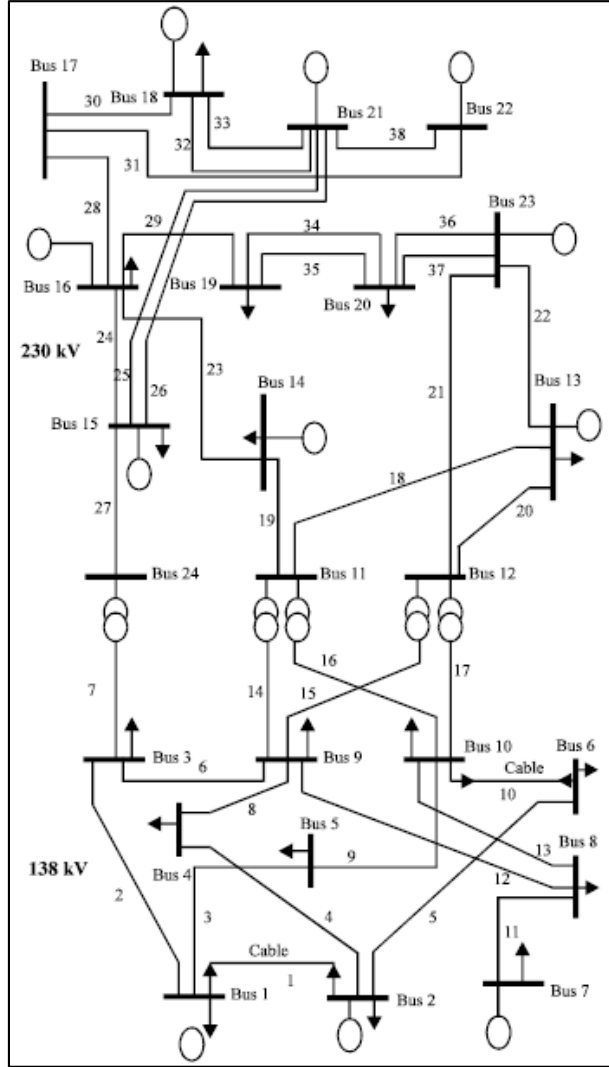


Figure 7. The IEEE One Area RTS-96 is the basis for the electrical power system Salmerón et al. (2004).

## 2. Milestone B

Milestone B is a combined Model (FM+EM) that consists of the two logical models and the real data. It allows us to solve the two models separately and in a combined manner.

We create a Python subroutine that uses Pyomo to build the combined logical model (FM+EM), which imports logical models FM and EM, defines links between models, and returns a separate logical model. Figure 8 shows the steps and inclusions per model.



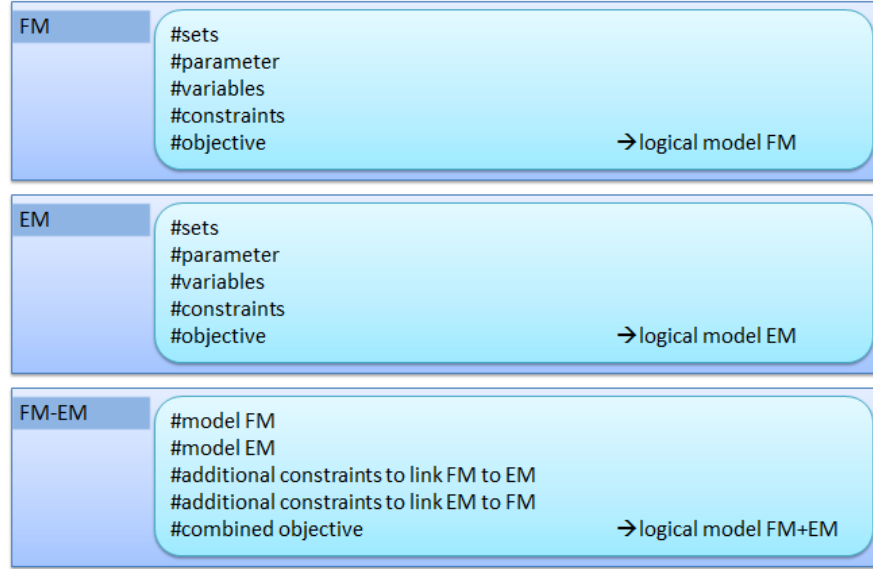


Figure 8. Logical models of fuel model, electric model, and combined model and their inclusions.

We create separate instances for model FM, model EM, and combined model FM+EM. This allows us to solve FM alone and to solve EM alone, but also to solve FM+EM independent of the single models.

*a. Comparison of Example Used in Dickenson (2014)*

The interaction options are shown in Figure 9 (electric network depends on fuel) and Figure 10 (fuel network depends on electricity) and are used in the same manner in the analysis of the interdependency study from Dickenson (2014).



The next two figures sum up the output and the results from the run of the combined model FM+EM in GAMS (see Figure 11) and in Python Pyomo (see Figure 12). They show the state of the objective values for the separate models after completion of the combined run in the structure used by Dickenson (2014). The baseline solutions of the three models are EM: 4460.3, FM: 79593.5, and FM+EM: 84053.8. These models use the same input files for all implementations. The specific values of flows differ between the implementations, but that is caused by the fact that there are multiple optimal solutions for the flows.



Figure 11. Output of flows and results from the base case for model FM+EM as implemented in GAMS.

Fuel Node	Supply Demand
FN1	112.5
FN2	100
FN3	100
FN4	450
FN5	100
FN6	100
FN7	100
FN8	0
FN9	100
FN10	0
FN11	100
FN12	-
FN13	285
FN14	100
FN15	285
FN16	535

Interdependent Node
Shut down to optimize cost
Independent Load Shed
x- Shed Forced by dependence

PYTHON

Generator Node	Gen Cap
g101a	10
g101b	10
g101c	76
g101d	76
g102a	10
g102b	10
g102c	76
g102d	76
g107a	80
g107b	80
g107c	80
g113a	95
g113b	95
g113c	95
g114	0
g115a	12
g115b	12
g115c	12
g115d	12
g115e	12
g115f	155
g116	155
g118	400
g121	400
g122a	400
g122b	50
g122c	50
g122d	50
g122e	50
g122f	50
g123a	155
g123b	155
g123c	350

Demand Node	Load
d101	108
d102	97
d103	180
d104	74
d105	71
d106	136
d107	125
d108	171
d109	175
d110	195
d113	265
d114	194
d115	317
d116	100
d118	333
d119	181
d120	128

Objective from Fuel-only model:	4460.3
Objective from Power-only model:	79593.5
Objective from Combo model:	84053.8

Figure 12. Output of flows and results from the base case for model FM+EM as implemented in Python Pyomo.

***b. Comparison of Two Examples of Stress on the Inter-dependency***

We simulate three situations to test the models and verify their results. The first one checks the functionality of the implementations, and the following two examples show, first, a case in which the GAMS and the Python Pyomo version have to find a single best solution to reroute the commodity of one network with high cost to satisfy demands.

(1) Case Zero: No Load Shedding Cost

We set the load shedding cost for both models to zero, as indicated in Table 1. We expect a reduction in total cost. We are testing basic functionality of both models with a known outcome.

Table 1. Load shedding costs in base case and in the test model.

Model	FM	EM	FM+EM
load shedding cost before	150	150	150
load shedding cost after	0	0	0

The effect is what we would expect because the optimization for minimal cost decides that there is no need to transport or satisfy demands at all. This was a critical finding in Dickenson (2014) because the search for an appropriate high penalty for load shedding was crucial to gaining realistic results. These results match the two implementations and concur with the expected outcomes (see Figure 13).

GAMS		Python	
Objective from FM:	0	Objective from FM:	0
Objective from EM:	0	Objective from EM:	0
Objective from FM+EM:	0	Objective from FM+EM:	0

Figure 13. Results of case zero in GAMS and Python models.

(2) Case One: Electric Generator Out of Order

In the first example, we assume an electric generator (g118) has malfunctioned and produces zero MWh instead of 400, as depicted in Table 2. We expect no influence on the FM, but a cost increase in the EM and the FM+EM, because the total power demand cannot be satisfied and load shedding cost should occur. We are testing the optimization process of both systems with an artificial test and a known, but non-obvious solution.

Table 2. Electric generator g118 has capacity of 0 instead of 400 MWh.

Model	FM	EM	FM+EM
capacity before	-	400	400
capacity after	-	0	0

All three models produce the same optimal results, and the effect is only in the EM and the FM+EM models. This test shows that both implementations solve the single and the combined model independent from each other. The penalty in EM is equal to the penalty in EM+FM because the system is still solvable in the way to avoid an additional penalty in the interdependent FM via the optimal routing in the separate EM, which was artificially chosen to test the optimization process. These results also match the two implementations and concur with the expected outcome tendencies (see Figure 14).

GAMS	
Objective from FM:	4460.3
Objective from EM:	93116.4
Objective from FM+EM:	97576.6

Python	
Objective from FM:	4460.3
Objective from EM:	93116.4
Objective from FM+EM:	97576.6

Figure 14. Electric generator is not producing energy and causes a 17% increase in cost in the EM.

### (3) Case Two: Fuel Arc Broken

In the second case, we assume a fuel arc (FN8-FN12) is broken and has zero capacity instead of 1350 bbl, as depicted in Table 3. We expect an influence on the FM because the highest supplier FN8 has to reroute its fuel to satisfy the demands within the network. We do not expect an effect on the interdependent electric network because the amount of fuel that can be transported has not changed. We are testing the optimization process of both systems.

Table 3. Fuel arc FN8-FN12 capacity of 0 instead of 1350 bbl.

Model	FM	EM	FM+EM
capacity before	1350	-	1350
capacity after	0	-	0

All three models produce the same optimal results, and the effect is only in FM and FM+EM. Every arc in FM has the same capacity and is set so that the highest supplier is able to send his product completely over any arc. This test shows that even in this comfortable case, the rerouting cost to avoid penalty forms demands within the system and penalty from the interdependent system can get relatively high (see Figure 15).

GAMS		PYTHON	
Objective from FM:	5612.8	Objective from FM:	5612.8
Objective from EM:	79593.5	Objective from EM:	79593.5
Objective from FM+EM:	85206.3	Objective from FM+EM:	85206.3

Figure 15. Broken fuel arc causes a 26% increase in cost in FM.

#### (4) Discussion

Both GAMS and Python Pyomo models give the same objective values and are able to solve the problems in a short amount of time. An evaluation of computation time can be performed only with more systems to be compared and with systems with more nodes or a higher complexity. Extreme cases occurring in fuel and in electric network on dependent nodes cause results represented in both models as intuitively suspected or artificially designed to test their reliability in function.

### 3. Milestone C

Milestone C consists of several improvements that seemed necessary in terms of usability, security, transferability, and usability of a backend simulation engine.

We adapted the GUI originally developed from the Infrastructure Design Editor Analyzer (IDEA) project (Johnson and Heine 2015) to work in a Microsoft (2015b). Windows 8.1 and therefore future systems. We managed the usage of a single backend server system to allow restriction of access to sensitive data.

We redraw the fuel network Alderson (2014) into the IDEA (Johnson and Heine 2015; see Figure 16) environment and programmed Python Pyomo (2015) code. This model uses a CPLEX (2015) solver but can technically use different solvers by changing only a single line of code.

An additional adaption was to store variations of the solution sets in a reasonable manner that, for a specific network, the user is able to switch between different input settings and immediately see the visualization on screen while also being able to extract the data for use in an arbitrary tool for further analysis or representation (JMP 2015, Microsoft 2015a, R 2015). The networks can be created and modified in the IDEA Editor (see Figure 16).

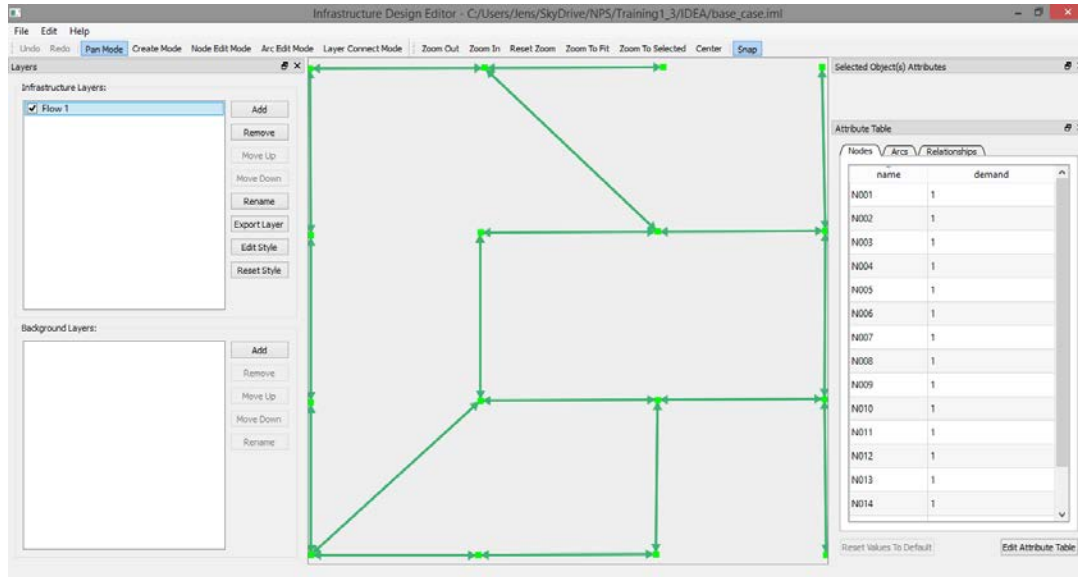


Figure 16. Screenshot of the IDEA Editor showing the creation of the basic fuel network.

The interaction between these two networks can now be executed with a single click on a “Run Simulation” button after loading them into the GUI. The flows are color



coded and can also be varied by the user, as depicted in Figure 17. The results proved to be equal to those obtained in Dickenson (2014).

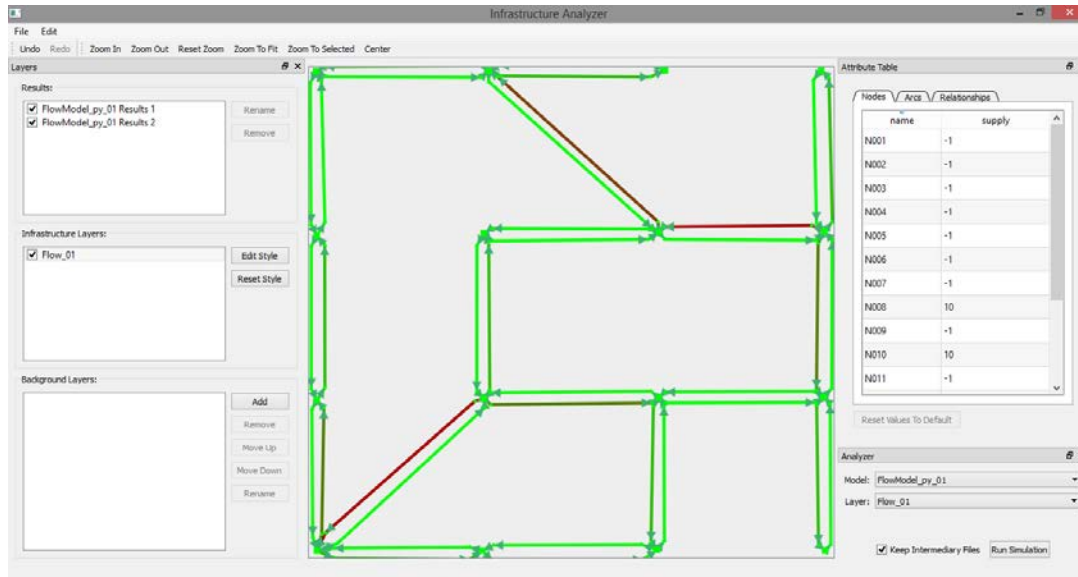


Figure 17. Screenshot of the IDEA Analyzers showing a solution for the basic fuel network without background in preset color coding for flows and the ability to compare results visually and via tables quickly.

In integration of a Dystopia (Center for Homeland Defense and Security [CHDS] 2011) network, layers from the provided server worked out well, and an integration of real-life data is possible. Figures 18 and 19 show the artificial island of Dystopia with rudimentary networks drawn already.

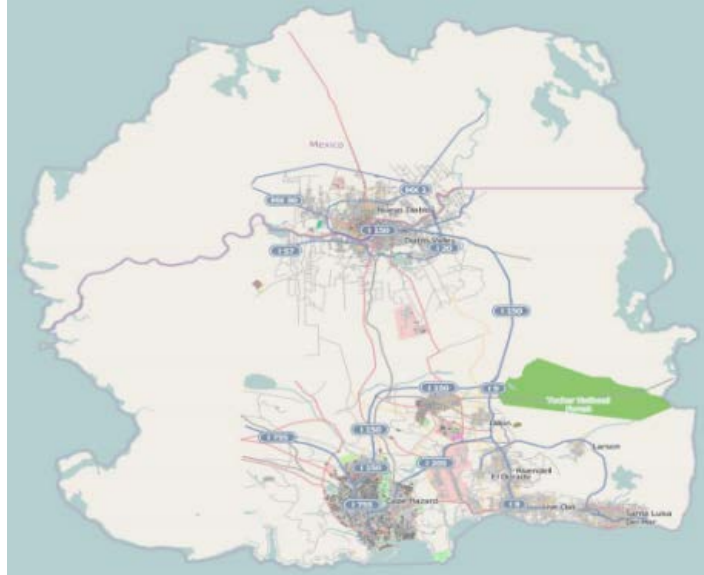


Figure 18. The Dystopia map from the Center for Homeland Defense and Security (2015) and its developed networks so far.



Figure 19. Screenshot of a Dystopia map used by Martin (2014) to show a partial network to visualize results to the background. The example here is a telecommunications network but is illustrative of the ultimate goal to connect models of interdependent CI systems in a geographically realistic environment.

To make integration in the user interface easier, we included a help file and a step-by-step example to the IDEA Editor so that the usage of this tool behaves more like

any other standard GUI and allows quick access to commonly asked questions and a convenient introduction for first-time users. The structure is shown in Figure 20 (without the 27 steps of the tutorial).

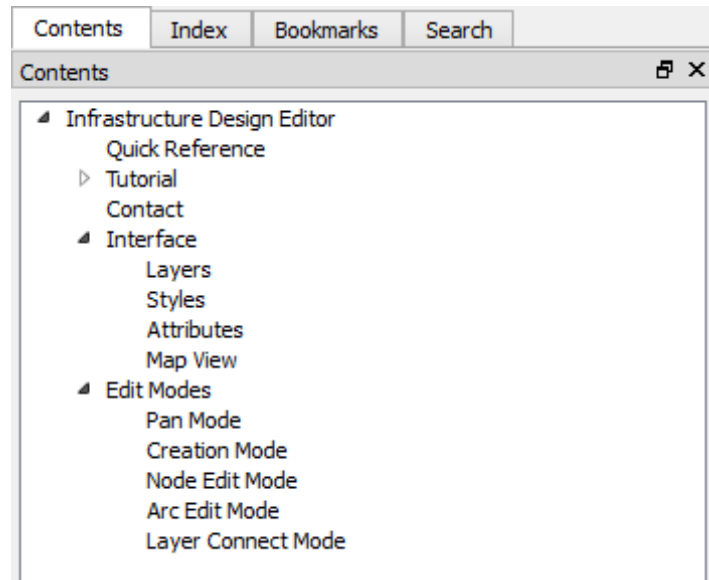


Figure 20. The structure of the IDEA Editor help file allows users to take a tutorial, find their topic on one site, and use the search option effectively.

## **V. SUMMARY AND CONCLUSION**

### **A. SUMMARY**

Our goal has been to create a user-friendly, adaptable basis for future analysis on interdependent CI networks. We accomplish several steps in that process. We replace multiple programming language solutions (GAMS, MS Excel, etc.) with a single freeware language (Python Pyomo). In the model, we allow any solver to be used and show the output with CPLEX. It is now possible to work from anywhere via a server on any recent Microsoft Windows system. The distribution of information is now controllable due to the backend solution. The intermediate files are reduced from over twenty to two and standardized in one globally usable format (XML). We code a functional CI fuel model. We code a functional CI electric model. We combine these models in a new model. Editing and visualisation via a GUI are now possible. Analysis becomes faster, more user-friendly, and in accordance with notional standards. Analysis modifications in the GUI are also more user-friendly, and their outcomes are provided in transferable files. The final models can be used to improve resilience of networks and find vulnerable spots in case of a possible disaster. This way, a blackout or loss of communication becomes less likely, and the chance of losing a high amount of human life can be reduced. Overall, our contribution allows easier access and faster analysis of interdependent CI networks.

### **B. CONCLUSION**

We transfer two non-trivial logical network models and their data into a single open-source programming language to allow future work to be implemented more easily. We make results transferable and enable the user to interact with the models via a GUI that gives visual feedback on results and has the opportunity to change settings and values quickly. With all the other improvements stated, we found a base for future studies that are not one-time results anymore, and we enhanced attractiveness for using it in education, research, and presentations.

### C. FUTURE WORK

To improve global usage, there is a need to develop models for other networks that might interact (e.g., telecommunication or transportation) with realistic behavior and a clear dependency link between the systems.

To improve the usage of our tool, we should expose students of OR, researching faculty, managers of CI, and decision-makers of cities/industry/military to the system and find out whether the visualization can be improved. We should also create a stack of more models and networks to do research and out-of-the-box experiments with the networks that are not real but represent the behavior of each system and its interaction in a realistic way.

To improve in terms of user-friendliness, it would be useful to create a tool similar to the editor and the analyzer that allows for creating scenarios without the need to manually enter every change into the data or the GUI, but rather set up rules to influence the network in cases of disruptive events like an earthquake, tsunami, or bomb attack, for example, via a separate Scenario Editor GUI (see Figure 21).

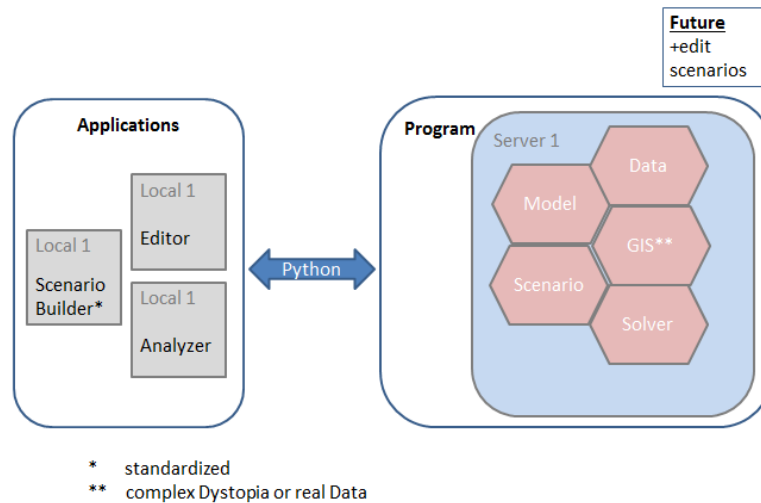


Figure 21. Future situation of data organization and applications including the Scenario Builder and a library of verified GIS (Geographic Information System) data.

Because our system allows integration of different algorithms in a convenient manner, we recommend testing and exploring different approaches, which is optimal for large-scale networks and a higher number of interacting networks. For example, to validate the results, a remote and known network of a feasible-sized infrastructure, like the electric and fuel power grid of the Hawaiian Islands, could be used in future studies.

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